COMPARISON OF A PHYSICAL AND NUMERICAL MOBILE-BED MODEL OF BEACH AND T-HEAD GROIN INTERACTION

BRIAN JOYNER[1], PAUL KNOX[2], ATILLA BAYRAM[3], LIHWA LIN[4]

1. *Halcrow Inc., 4010 Boy Scout Blvd., Suite 580, Tampa, FL, 33607,USA. bjoyner@halcrow.com*
2. *National Research Council of Canada, Canadian Hydraulics Centre, 1200 Montreal Road, Building M-32, Ottawa, ON, Canada, K1A 0R6. paul.knox@nrc.ca*
3. *Halcrow Inc., 22 Cortlandt St., New York, NY, 10007, USA. abayram@halcrow.com*
4. *U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199,USA. Lihwa.Lin@usace.army.mil*

Abstract: The Coastal Modeling System (CMS) numerical model is applied to simulate nearshore planform and beach profile morphology changes during storm wave and water level conditions on a sandy beach stabilized by T-head groins. The numerical model results are compared to measured planform and profile changes from a 1:25 scale, three-dimensional mobile bed physical model study of the beach and T-head groin system. Numerical simulations and comparisons are done at prototype scale. At present, the numerical model calculates well the wave propagation toward the shore and morphology change shoreward of T-head groins. It is evident that there is a need to include the swash zone process, wave asymmetry and undertow to improve the sediment transport calculation in area between the seaward ends of T-head groins

Introduction

Numerical modeling technology for simulating beach morphology in the presence of complex structures is advancing rapidly, though limitations remain in the ability to simulate detailed beach contour movement near and above the water line. Mobile-bed physical models are also limited, primarily due to issues of model scale constraints. The primary aim of this paper is to compare the performance of a numerical coastal morphological model with a series of physical model tests, for an open-coast sandy beach modified with T-head groins. It is important to understand the relative benefits available through applications of the combination of numerical and physical models to projects. The present study compares planform and profile changes in the physical model with simulations using the Coastal Modeling System (CMS) numerical model (http://cirp.usace.army.mil/wiki/CMS).

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14. ABSTRACT
The Coastal Modeling System (CMS) numerical model is applied to simulate nearshore planform and beach profile morphology changes during storm wave and water level conditions on a sandy beach stabilized by T-head groins. The numerical model results are compared to measured planform and profile changes from a 1:25 scale, three-dimensional mobile bed physical model study of the beach and Thead groin system. Numerical simulations and comparisons are done at prototype scale. At present, the numerical model calculates well the wave propagation toward the shore and morphology change shoreward of T-head groins. It is evident that there is a need to include the swash zone process, wave asymmetry and undertow to improve the sediment transport calculation in area between the seaward ends of T-head groins.

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Physical Model Description

The physical model is based on a proposed shoreline development project to include, among other features, nourishment and maintenance of an approximately 7km long stretch of the barrier island and construction of several emergent T-head groins (Figure 1). The three-dimensional physical model was undertaken at a geometric scale of 1:25 at the Canadian Hydraulic Centre's Large Area Basin (LAB), utilizing a set of moveable wave generators capable of providing long-crested waves to match a variety of spectral conditions. Tests from three dominant design wave directions were conducted to investigate the performance of the proposed design under storm wave and water level conditions. Wave heights were measured at several wave probes, some of which are indicated by the labels in Figure 2.

A fine silica sand with a median diameter of approximately 0.13mm was employed in the model to represent the beach fill. This sand was the finest non-cohesive material readily available. According to the expression for fall velocity developed by Soulsby (1997), the 0.13mm sand has a fall velocity of 1.1cm/s. Applying the Froude scaling law for velocity, this material represents prototype median grain diameter of 0.39mm with a fall velocity of 5.7cm/s. The model beach fill was constructed to crenulate shaped planforms in the bays between T-groins based on GENESIS (Hanson, 1989) simulations of typical annual transport at the site. The initial model profiles were constructed to a 1:10 slope above the Mean Sea Level (MSL = +1.32mMLLW) and 1:25 slope below MSL. The mobile bed portion of the model ranged from the -2mMLLW contour offshore to the +4mMLLW contour on land (Figure 2).

This study focuses on the first series of wave tests to limit uncertainty due to rebuilds of the model bathymetry that were carried out between wave test directions. The incident waves have the direction of most severe storm waves at the project site (285^{O}N), equivalent to a 20^{O} counterclockwise angle from shore-normal. The waves in the physical model were selected to match the intensity, profile, and duration of a realistic design storm as in Table 1 and Figure 3. After the model beach was constructed, a small wave segment was run in the model for a short duration (8-hr prototype scale) to smooth out any small aberrations remaining from the construction. The beach was then in its initial condition, t=0 hr.

Beach profile morphology was measured after each wave segment on a transect between Groin 3 and Groin 4 for each test case. Measurement of the beach profile was conducted manually from a bridge as shown in Figure 4. The location of the transect (Profile 2) is shown in Figure 2. Planform morphology was measured within the mobile bed area of the model at the end of the full set of tests from a given wave direction.

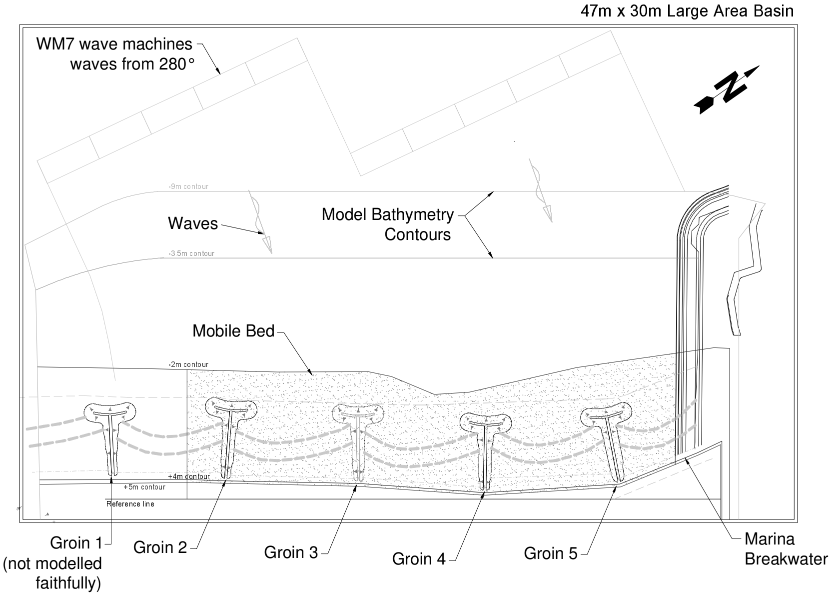

Fig. 1. Schematic of physical model setup in CHC Large Area Basin (LAB).

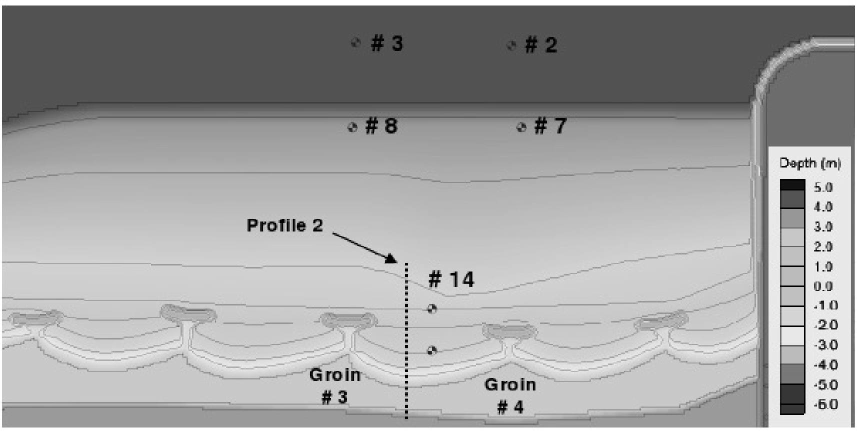

Fig. 2. Numerical model initial bathymetry and locations of selected wave observation points corresponding with physical model wave probes.

Table 1. Physical and numerical model water level and wave test conditions at -5mMLLW contour.

Storm Segment	Water Level (m MLLW)	H_{m0} (m)	T_p (s)	Duration (hr)
Work-in period	+1.90	0.72	4.0	9
Operational Conditions	+1.90	0.72	4.0	40
1-year return period storm	+2.02	2.06	6.7	12
50-year return period storm	+2.10	3.20	8.4	10
100-year return period storm	+2.17	3.50	8.7	9
10-year return period storm	+2.04	2.75	7.8	11

Numerical Model Description

The Coastal Modeling System (CMS) is an integrated numerical modeling system for simulating waves, current, water level, sediment transport, and morphology change. A CMS numerical model was applied to mimic the initial bathymetry and the series of wave and water level cases as conducted in the physical model. CMS utilizes a steady-state spectral wave transformation model, CMS-Wave (Lin et al. 2008), with parametric diffraction and reflection, and the time-dependent hydrodynamic / sediment transport model, CMS-Flow (Buttolph et al. 2006), to calculate the morphology change. The user may select either equilibrium or non-equilibrium sediment transport routines for the morphology simulation, and the model is developed in both an explicit and implicit solver formulation. CMS is applicable for predicting sediment transport and bed morphodynamics in the presence of coastal structures. However, it is recognized that the release version of the numerical model is not at present directly applicable to predicting beach morphology above the swash zone. For this reason, the study is presently limited to comparing the planform and profile morphology for submerged areas.

The numerical model was set up on a horizontal grid resolution of 4m by 4m in the offshore regions and a resolution of 4m alongshore by 2m cross-shore within and immediately offshore of the T-head groin bays. Waves were simulated in the CMS by applying time varying spectra at the offshore boundary. The input waves were generated as TMA spectra with a directional spreading index of 30 (Hughes, 1985) and the wave heights listed in Table 1. The wave model was coupled with the flow and transport model at an interval of 2 hr. Simulations presented herein utilized parametric diffraction (with intensity factor = 1) and the wave breaking formulation of Battjes and Janssen (1978). Several configurations of the CMS-Wave parameters were tested, and it was found that (a) the Battjes and Janssen breaking formulation gave the most realistic matching with waves measured in the physical model, and (b) the CMS-Flow calculations were not sensitive to reasonable variations in bed roughness and parametric reflection allowances within CMS-Wave.

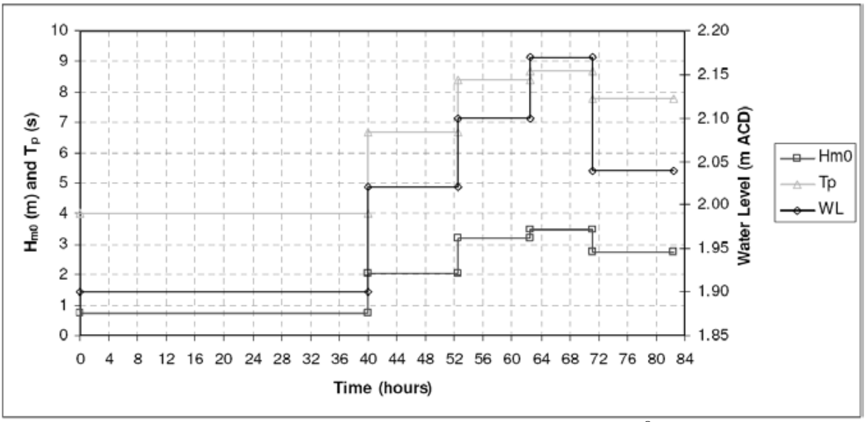

Fig. 3. Physical model wave and water level test signals for 285^{O}N storm set.

Fig. 4. Physical model oblique view showing profile measurement location and bridge.

The T-head groins and the shore-normal breakwater trunk at the model's east end were simulated as non-erodible bed ("hardbottom"). Within CMS-Flow, deposition of sediment is allowed over hardbottom areas, but the bed is not to be eroded below the specified hardbottom elevation – specified as the initial bathymetry elevation. The grid cells offshore of the -2m MLLW contour were also simulated as hardbottom, since the areas seaward of -2m MLLW did not have a mobile, erodible bed in the physical model. A mean sediment grain size of 0.39mm was utilized in the numerical model corresponding to the prototype scale of the physical model sediment. Bottom roughness was represented in the flow and wave models by a Manning's n=0.025.

CMS-Flow is formulated in both an explicit solver version and a relatively new beta implicit version. Sediment transport calculations may be conducted using one of several available equilibrium total load (EQ-TL) or non-equilibrium transport (NET) formulations. Results of initial simulations led this study to focus mainly on the explicit version of CMS-Flow, and final simulations were conducted using EQ-TL Lund-CIRP transport formulation and the NET formulation. A single simulation utilizing the implicit solver is presented. Table 2 gives details of the CMS-Flow formulations and sensitive parameters for the numerical model results presented.

Table 2. Numerical model formulations and selected model parameters.

	Model 1	**Model 2**	**Model 3**
Engine type	Explicit	Explicit	Implicit
Transport formulation	EQ-TL	EQ-TL	NET
Suspended load scale factor	1.5	2.0	2.0
Bed load scale factor	1.5	2.0	2.0
Bed slope coefficient	8.0	8.0	8.0
Morphology acceleration factor	2.0	2.0	2.0

Results and Discussion of the Morphodynamic Response

The morphologic response of the physical model shoreline shed much light on the potential response of the prototype beach, and this information was used to improve the detailed project design and highlight operational risks associated with high energy storms. The tests also revealed essential information with respect to the potential current and sediment pathways, and the subsequent response to the shoreline for a representative array of wave conditions. However, the scope of this paper is limited to the comparison with the numerical model with respect to the planform bed contour response between groins #3 and #4 and the nearshore profile response at the single transect location within that groin bay.

Figure 5 compares the numerical model waves to the measured physical model waves at the physical model wave probe (#14) closest to groins #3 and #4. The numerical model replicates the measured wave almost identically from time t=54 hr onward, during the most severe waves of the test series. The numerical model waves are significantly overpredicted between t=40 to 54 hr. The incident offshore waves during this period have H_{m0}=2.06m, and the water depth at probe #14 is approximately 3.5m during this period. It is noted that little transport and morphology change was observed in either model during this period of time where the numerical and physical model waves diverge.

Model 1 – Explicit solver, Equilibrium Total Load transport formulation

Calculated changes in beach profiles and bed contours are compared with the morphology observed in the physical model. Figure 6 gives the measured planform morphology from the physical model at time t=82 hr; the background shaded colors indicate the initial model bathymetry at t=0 hr. Figure 7 shows the numerical Model 1 bed contours at t=82 hr with respect to the physical model contours. The white-shaded labels indicate physical model contours, while the bold non-shaded labels indicate numerical model contours. Some of the general trends observed in the physical model – offshore migration of the -2mMLLW contour; strong landward movement of the contours above 0mMLLW; rotation of the contours to alight with the wave direction in the downdrift half of the groin bay – are replicated in the numerical model. However, the numerical model predicts a submerged accreted area in the center of the groin bay that is counter-intuitive and not reflected in the physical model. To improve the CMS performance in this area, it is necessary to investigate the effects of wave asymmetry and undertow to the sediment transport. The improvement of CMS shall also include the three-dimensional simulation, because the sediment transport near T-head groins could be quite different from the surface to bottom layers as a result of wave, current, and structure interaction.

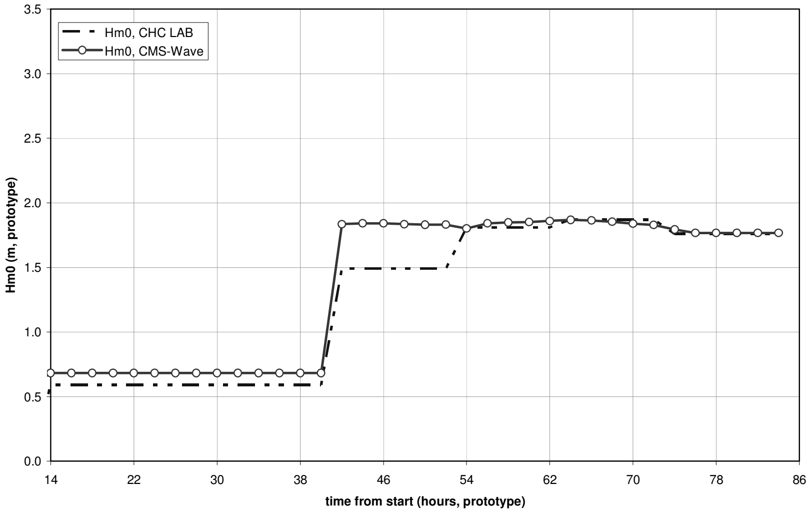

Fig. 5. Physical model wave conditions near groin head at wave probe #14, with numerical model waves using Battjes and Janssen (1978) breaking formulation.

In addition, the physical model shows a seaward migration of the -1.0m and -0.5m MLLW contours in the updrift half of the groin bay. The numerical Model 1 does not produce this "bump" in the -1.0m and -0.5m contours at the downdrift side of the groin head. However, the numerical model does produce a similar "bump" in those contours nearer the updrift side of the groin head. Coupled with the observation that the numerical model produces generally less erosion than the physical model, in the center and downdrift areas of the bay especially, it is supposed that the reduced supply of sand available for bypassing the groin head causes the seaward "bump" shape to occur further updrift in the numerical model than in the physical model.

Figure 8 shows profile bed elevation change along the transect for both the physical model and numerical Model 1 at t=82 hr. The physical model beach profile was measured only at Profile 2; however, numerical model results are presented at both Profile 2 and Profile 1 to provide an understanding of the spatial variability in the computed morphology. In the figure, bed elevation change is on the left y-axis,

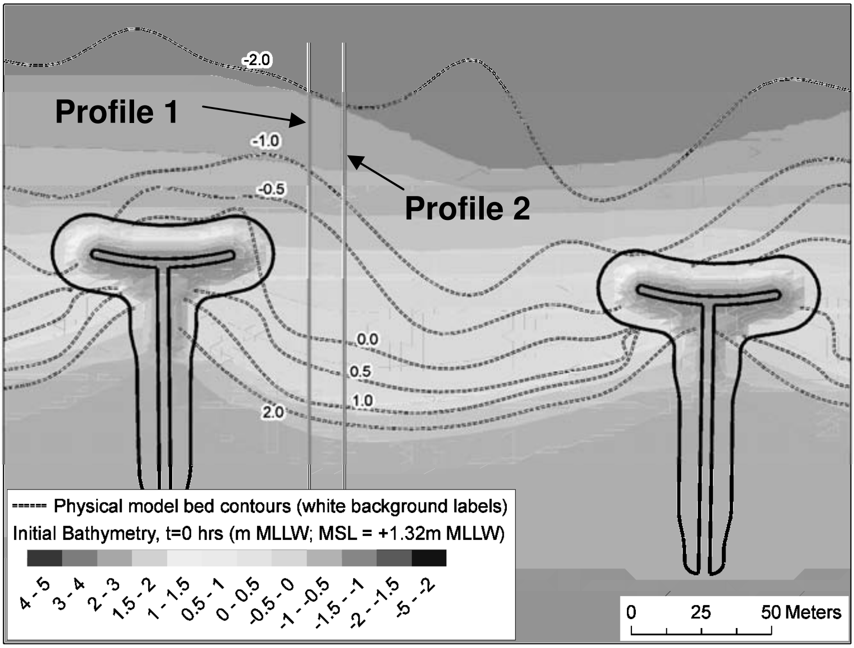

Fig. 6. Physical model plan morphology at time t=82hr vs. initial model bathymetry

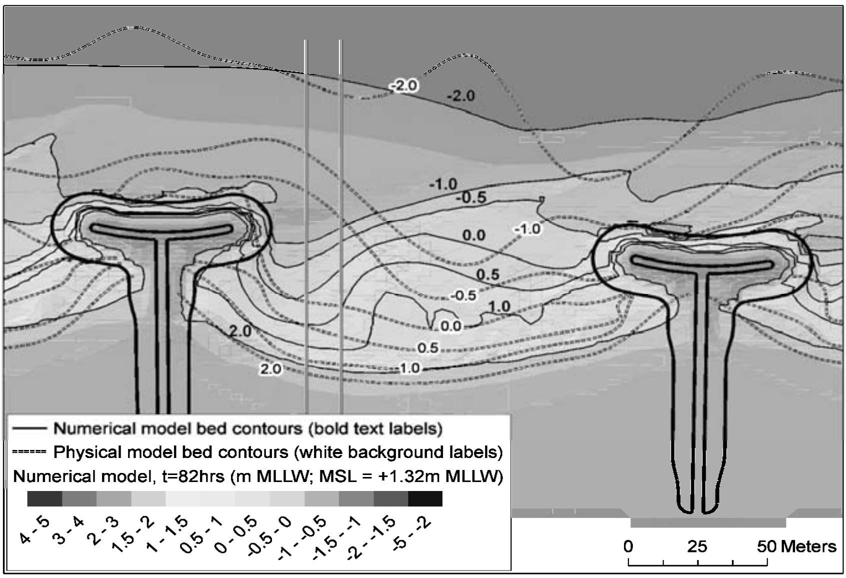

Fig. 7 Numerical Model 1 plan morphology vs. physical model at time t=82hr.

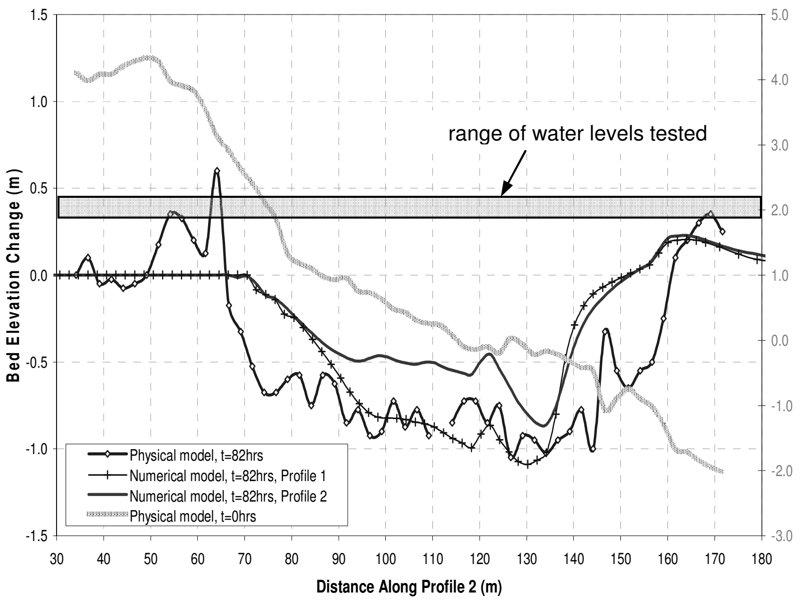

Fig. 8. Numerical Model 1 Profile 1 and 2 morphology vs. physical model at Profile 2.

while the hatched grey line (right y-axis) indicates the initial bed profile as a visual reference. The red solid curve is Model 1 at Profile 2; the blue crossed curve is Model 1 at Profile 1; and the brown diamond-marked curve is the physical model at Profile 2. The general trends and slopes of vertical bed change are similar between the numerical and physical models between station 85 to station 135 and to a lesser extent from station 140 to station 160. The numerical model does not predict as much vertical erosion at Profile 2, though more similar vertical erosion is predicted in the numerical model at Profile 1 (13m toward the updrift groin).

Model 2 – Explicit solver, Equilibrium Total Load transport formulation

Figures 9 and 10 display the morphology results for Model 2. The primary difference between Model 2 and Model 1 is the increase of bed load, suspended load, and morphology acceleration factors to 2.0. Increase of these factors required a decrease in the hydrodynamic, transport, and morphology update time steps in order to maintain morphodynamic stability. Model 2 produced a submerged planform and beach profile more similar to those measured in the physical model. The measured mid-bay erosion was more prevalent and the magnitude of bed change (erosion) along the profile was more similar to the physical model.

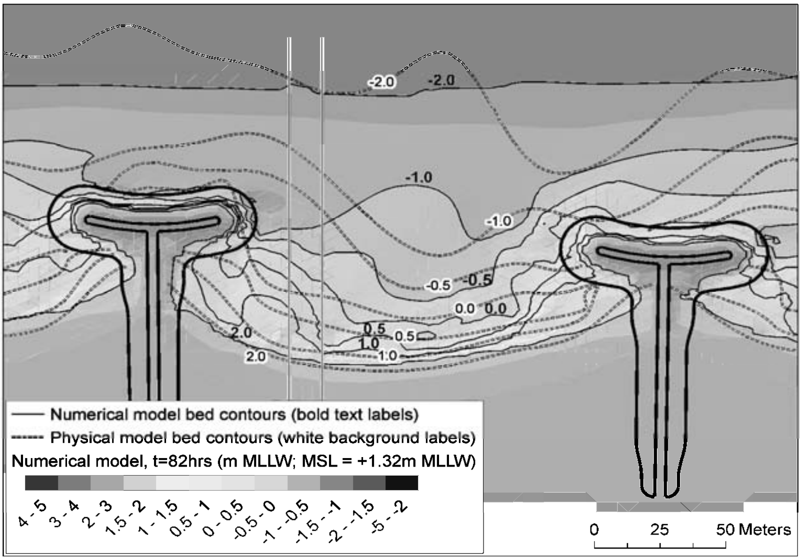

Fig. 9. Numerical Model 2 plan morphology vs. physical model at time t=82hr.

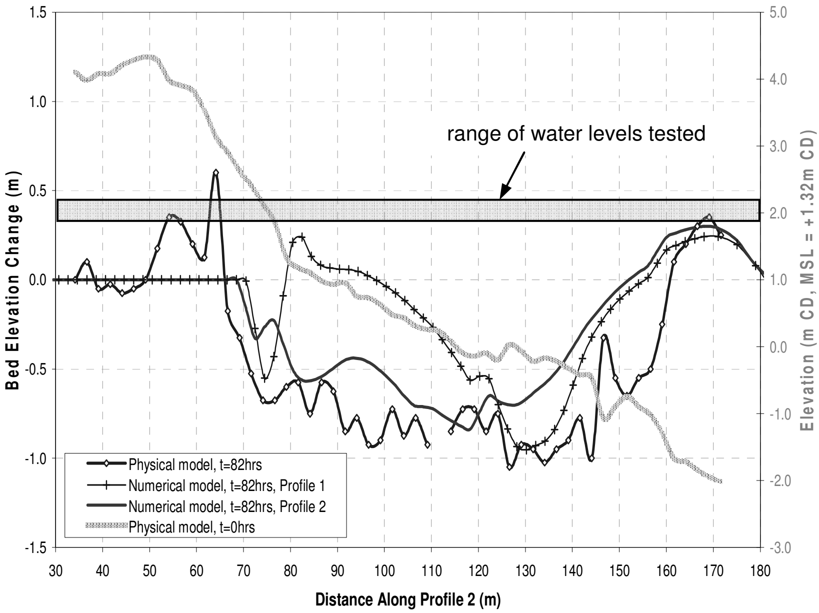

Fig. 10. Numerical Model 2 Profile 1 and 2 morphology vs. physical model at Profile 2.

Model 3 – Implicit solver, Non-Equilibrium (NET) transport formulation

Figures 11 and 12 display the morphology results for Model 3. The difference between Model 3 and Model 2 is that Model 3 was conducted in the implicit version of CMS-Flow using the NET Lund-CIRP transport formulation. The planform morphology is smoother than that resulting from Model 1 and Model 2, but the degree of contour recession measured in the center of the groin bay is not reproduced as well in Model 3. The seaward “bump” in the -1.0m and -0.5m contours is a bit more noticeable in Model 3, but it remains significantly updrift of the similar features in the physical model. The profile morphology (Figure 12) reinforces the observation that Model 3 produced significantly less erosion of the beach than measured in the physical model – while approximately the same vertical bed change occurred near the land/water interface (station 70m), that eroded sediment appears to have been deposited into a bar between stations 80m to 90m. Interestingly, the Model 3 profile morphology seaward of station 110m is more similar to the physical model than either Model 1 or Model 2.

Conclusions

The CMS numerical model system, consisting of the coupled CMS-Wave and CMS-Flow computational engines, was used to simulate a series of three-dimensional mobile bed scaled (1:25) physical model tests. The numerical model simulations were conducted at prototype scale and compared to measurements from the physical model (scaled to prototype). The numerical model successfully replicated the wave heights measured in the physical model, with minimal error for the most significant test segments. The wave breaking calculation in the simulation is based on the formula by Battjes and Janssen.

The CMS-Flow explicit solver version and a beta implicit version were applied for the sediment transport and morphology change calculations. However, significant departures from the CMS-Flow software “default” values for suspended load factor, bed load factor, morphology acceleration factor, and slope coefficient were required to approximate the physical model morphology. The present version of CMS requires careful calibration of the above parameters to simulate the interaction of a sandy beach with T-head groins. At present, the explicit solution with EQ-TL Lund-CIRP transport formulation is more recommended for similar project applications where the shallow submerged contour change is of primary interest. The NET transport formulation produced generally smoother morphology, but it did not predict the magnitude of morphology change as well as the equilibrium Total Load within approximately 100m of the land/water interface. The NET transport did produce bed changes closer to the physical model at offshore positions parallel to and seaward of the T-heads.

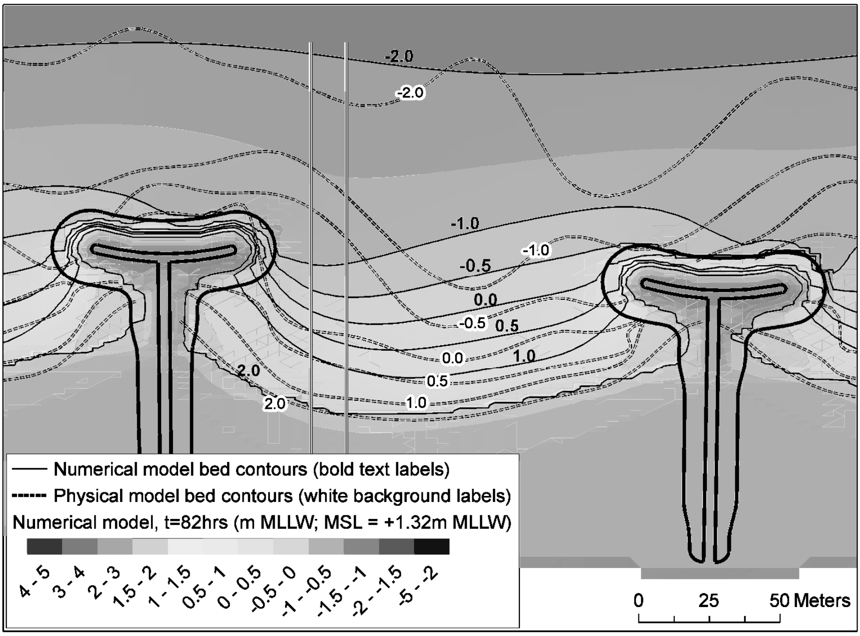

Fig. 11. Numerical Model 3 plan morphology vs. physical model at time t=82hr.

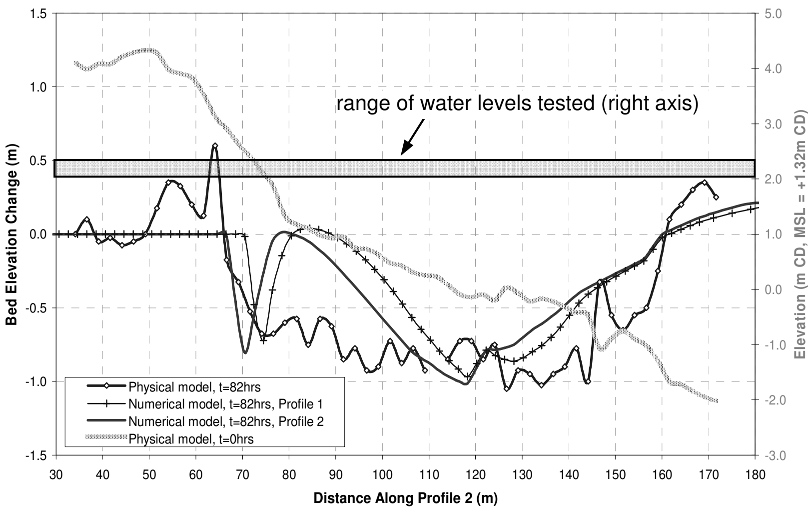

Fig. 12. Numerical Model 3 Profile 1 and 2 morphology vs. physical model at Profile 2.

Adjustment (increase) of the load factors and morphology acceleration factor within CMS-Flow required a decrease in the hydrodynamic, transport, and morphology update time steps in order to morphodynamic stability.

It is expected that the currently ongoing development of the CMS engines – including swash zone processes, wave asymmetry and undertow effects, as well as three-dimensional simulation – will greatly improve the numerical model's performance in similar project applications.

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